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| Patentanmeldung Nr. | Patent application No. | Demande de brevet n° |

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Patent specification:

Process and device for generating extreme ultraviolet radiation

5   Applicant:
Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.

Description

10   **Technical field**

This invention relates to a method and a device for generating extreme ultraviolet (EUV)-radiation according to the preambles of claims 1 and 2. Preferred application are those which require ultraviolet radiation or x-rays with wavelenghts of roughly 10 nm, as, for example, in EUV-lithography. In this field cheap and long-living x-ray sources are
15   needed which are disclosed in this application.

Background art

DE 197 53 696 A1 describes a device and a process for generating short wave radiation having a wavelength of for example 13 nm. The gas discharge takes place in an electrode system having two electrodes, each having an opening on the symmetry axis.
20   With suitable electric pulses a plasma is generated close to the openings. The plasma is cylindrically pinched and heated. Depending on the gas between the electrodes radiation with the characteristic wavelenghts is emitted.

Disclosure of the invention

The invention consists in a method and a device for generating extreme ultraviolet
25   (EUV)- radiation. The invention is described in detail in the following 26 pages.

Fig.1 discloses a minimal electrode system according the present invention, with a cathode (1), an anode (2) and electric isolators (6). Anode and cathode each have one opening (3, 4) which define a symmetry axis (5). This is the same minimal geometry as in german patent application DE 197 53 696 A1 which reveals a device and a process to generate short wave radiation with a wavelenght of roughly 13 nm. The discharge takes place between the electrodes (1) and (2). Suitable electric pulses generate plasma in the vicinity of the openings (3, 4) which is pinched towards a column and heated.

According to the present invention, the following improvements are possible:

Auxiliary electrodes behind the openings of the major electrodes (1, 2) improve the ignition of the discharge. If a positive voltage is applied to the auxiliary electrode behind the negative charged major cathode (1), the ignition voltage of the gas discharge is increased. This can also be used to increase the gas pressure with the ignition voltage being kept constant. In this way a higher energy and/or a higher density of particles can be achieved, which both lead to a higher intensity of the emitted radiation. If the voltage applied to the auxiliary electrode is changed on a short time scale, the major gas discharge can be ignited at a definite time. This is called triggering. Triggering is favourable to get stable or constant emission of radiation from the device.

Furthermore it is possible to increase the distance between the major electrodes (1) and (2) and to add additional electrodes between the openings of the major electrodes (1, 2). These auxiliary electrodes must have an opening on the symmetry axis (5), such that a longer plasma column can be formed which yields a higher intensity. Furthermore and even more important, a longer pinch plasma (several centimeter) is able to emit coherent, short-wave radiation by means of stimulated emission of radiation. This is are so far only known from capillary gas discharges.

DE 197 53 696.4 reveals electrodes each having one electrode, but it is possible to use electrodes each having more than one opening. As an example, electrodes (1) and (2) have a series of small openings arranged in a circle, with the center of the circle on the symmetry axis (5). When all plasma columns are ignited at the same time, all plasma columns from the electric pulse are accelerated towards the symmetry axis and form a pinch plasma on this axis. Simultaneous

ignition of the individual plasma columns can be achieved with the above-mentioned auxiliary electrodes. It is also possible that each electrode has one ring-shaped opening instead of many small openings. In both ways a free choice of the initial radius of the plasma is possible. This is more efficient than the solution of DE 197 53 696 A1 where only the diameter of the opening can be changed. In both ways the achieved particle density can be influenced in such a manner that a higher efficiency for the generation of radiation can be obtained.

DE 197 53 696 A1 describes the electric circuit as a damped oscillating discharge of a capacitor. In this case, the operator has two parameters to adapt the electric current to the plasma dynamics. These parameters are the maximum amplitude of the electric current and the cycle duration. Because of the fact that the plasma dynamics also changes the electric properties of the gas discharge on a very short time scale, for example within 10 nanoseconds, adapting the electric current according to the the plasma dynamics is favourable. This can be achieved by using a pulse forming network (PFN).

In one embodiment the PFN consists of an electric circuit which contains a collection of capacitors storing energy. The energy may be transferred directly to the electrodes. In addition, at least one extra condensator may be connected to this system via one or several saturable magnetic switches. By appropiate use of the switches, for example immediately before the plasma in pinched and starts to emit radiation, extra energy can be inputted, leading to increased emission of radiation.

Another possibility to get a more intensive radiation is varying the time which is needed to raise the voltage applied to the electrode system. By means of pulsed charging of the condensator connected to the electrode system the plasma can emit at higher gas pressures. This leads to a more efficient use of the gas discharge, and particularly to higher intensities.

DE 197 53 696 A1 report a roughly homogeneous gas density within the electrode sytem. An improvement, particularly concearning the propagation of the radiation towards the window where the radiation leaves the electrode system, is achieved by an influx and sucking off of different gases at different places within the electrode system. On the one hand this decreases

absorption within the electrode sytem, on the other hand more gas needed for the emission can be positioned where the gas discharge is located. Furthermore, gas having a high coefficient of transmission can be positioned in the other parts of the system. It can be favourable to work with a mixture of gases with gases having a high number of protons (xenon for example) which are needed for the gas discharge, and with gases having a small number of protons (helium, deuterium or hydrogen for example). With such a gas mixture, the ignition voltage of the gas discharge can be changed to values more favourable for emission of radiation.

Claims

5   1) Process for generating extreme ultraviolet (EUV)-radiation and soft x-rays from a gas
     discharge, comprizing the steps of applying a voltage to the electrode system, in
     such a manner that a gas discharge occurs which emits light in the EUV- or x-ray-
     region.

     2) Device for generating extreme ultraviolet (EUV)-radiation and soft x-rays from a gas
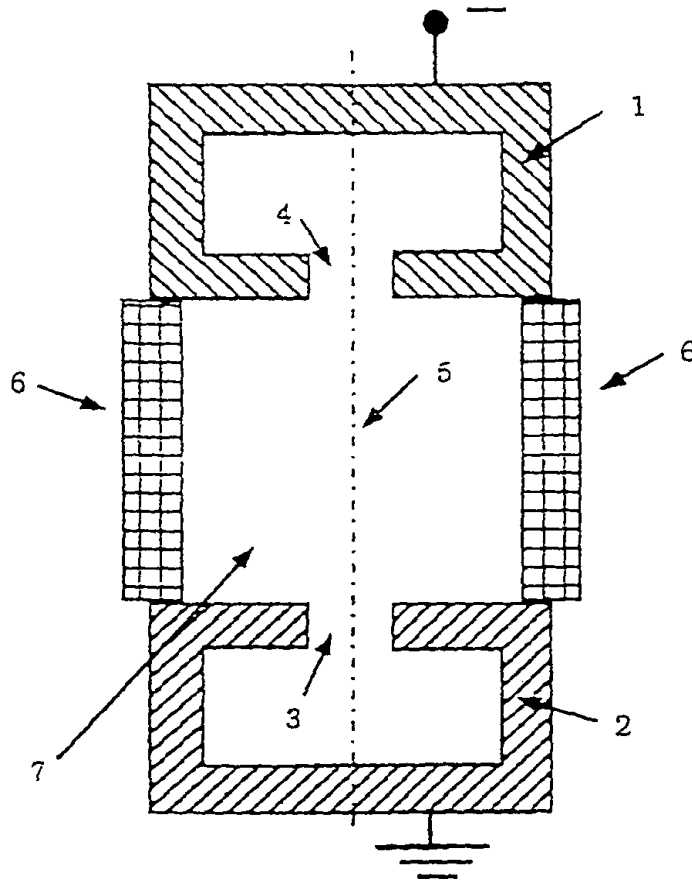10   discharge, characterized in an electrode system having at least two electrodes.

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Fig. 1 :

AN EXTREME ULTRAVIOLET RADIATION SOURCE
BASED ON A GAS DISCHARGE PLASMA

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Abstract

An extreme ultraviolet radiation source that emits in the spectral range around 13 nm wavelength or 100 eV photon energy is discussed. The source is based on a small pinch plasma which is generated in a fast discharge of electrically stored energy in the range of 1 Joule. Theoretical considerations are presented which show that this energy is close to the minimal required energy for a dynamic pinch plasma which effectively emits radiation in the spectral range of interest. Here, the constraints given by the gas discharge apparatus have to be taken into account. These constraints refer to, e.g., the length of the plasma column or the achievable compression or number density.

In this paper detailed theoretical considerations concerning such minimal gas discharge plasma are presented. The results are compared to experimental data of a plasma generated in a 1J discharge. Details concerning the design of the gas discharge apparatus will be published elsewhere [6].

The special design of the electrodes allows for omitting a switch between the electrodes and the storage capacity and for a low inductive coupling of the electrical power to the plasma. Thus storage energies in the range of 1 J and even below are sufficient to create current pulses in the range of several kiloamperes. Such pulses are required to compress the plasma to densities and temperatures leading to emission of radiation in the EUV range.

I. INTRODUCTION

Reducing the structure sizes in future semiconductor devices far below 100 nm requires new techniques, which will be the successor of the current deep ultraviolet lithography. A promising candidate for this „Next Generation Lithography" is the extreme ultraviolet lithography (EUVL), where a system of Bragg-mirrors is used to image a mask onto a photo resist at a wavelength around 13 nm. This technique requires radiation sources which emit several W/2πsr at this wavelength into a bandwidth of about 2 % [1]. Synchrotron and plasma based radiation sources are under discussion. where the main interest has been focused onto laser produced plasma sources.

Although gas discharge based sources have been known as emitter in the EUV-range for a long time. the interest to investigate them as possible radiation sources for EUV-lithography has increased in the recent past. Different concepts are reported in the literature, where topics relevant for EUVL like spectral emission characteristic, conversion efficiency. source size. repetitive operation. pulse to pulse stability or lifetime are considered. These concepts are for example the capillary discharge [2,3], the gas puff z-pinch [4] or the dense plasma focus [5].

There are already promising results concerning few demands but there is still work to be done for the fulfilment of all requirements given by EUV-lithography. Especially. improvements concerning lifetime and repetitive operation in the kilohertz range are necessary. These problems seem to be the easier solvable. if the plasma is generated with an energy or a peak power as small as possible that is released in the electrode system.

II. MINIMAL PINCH PLASMA SOURCE

The considerations concerning a minimal plasma emitting effectively in the extreme ultraviolet range are based on a dynamic pinch plasma. In such plasma a cylindrical column of gas is compressed and heated by the self magnetic field of a pulsed current. The main energy contribution for such plasma is assumed to origin from the ion kinetic energy which is accumulated in the compression phase of the plasma column. This energy is converted to thermal ion kinetic energy that is used to heat up the electron gas to the required temperatures. The plasma subsequently decays due to hydrodynamic expansion which will also determine the duration of the emission.

The discussion is generalised to the question of effectively emitting at a photon energy, $h\nu$, to make the results comparable to the comprehensive knowledge about pinch plasmas emitting at shorter wavelengths compared to 13 nm. The required energy for a plasma column with radius. r_p. length. l, ion density. n_i, and an electron temperature. T_e, is given by :

$$E_{pla} = \left\{ (\langle Z \rangle + 1)T_e + E_{pot} + h\nu \right\} \pi r_p^2 l n_i \quad (1)$$

The expression in brackets is the required energy per ion in the plasma. $\langle Z \rangle$ is the degree of ionisation. E_{pot} is the potential energy of the ionisation level and the contribution $h\nu$ expresses the energy for at least one excitation of each ion necessary for emission of a photon. With the aim to express the energy in equation 1 as far as possible in terms of the photon energy some assumptions have to be made.

The electron temperature is approximated by $T_e = h\nu / 3$.

which is also in good agreement with Wien's law for the maximum of the spectral brightness in dependence of temperature and photon energy for a thermal emitter

Without loosing generality the relation between the photon energy and the ionisation level is based on the discussion of the emission of hydrogen-like ions. In this case. the degree of ionisation. $<Z>$, can be expressed by the atomic number, Z, and the photon energy is given by $hv = 3/4\ Rv\ Z^2$ the Lyman-α line. The potential energy can be approximated by $E_{pot} = Rv\ Z^{2.5}$ ($Rv = 13\ 6\ eV$). These assumptions will lead to an estimation for the minimal required energy per ion (hv, E_{ion} in [eV]) :

$$E_{ion} \approx 1.52 * hv^{5/4} \qquad (2)$$

This energy is converted to radiation by collisional heating. ionisation and excitation in the plasma and determined by the number density. Effectively converting the ion kinetic energy requires a minimal number density or according to eq. 1 a minimal total number of ions.

The estimation of the minimum number of ions is based on the assumption that the time constant for ionisation into the required level, τ_{ion}, is of the same order of magnitude like the lifetime of the pinch plasma :

$$\tau_{ion} = r_p\ /\ \upsilon_{th} \qquad (3)$$

Here, the lifetime is approximated by the quotient of the plasma radius and the thermal ion velocity, v_{th}, which is usually assumed for thermal plasma expansion. Assuming $= 0.5\ v_s$, where v_s is the velocity of the collapsing plasma column, one can estimate this velocity by eq.2 and the relation for the ion kinetic energy ($E_{ion} = 0.5\ m_i\ v_s^2$, ion mass). Taking the time constant for ionisation from Ref. [7] equation 3 leads to an estimation of a minimal value for the expression $n_i\ r_p$ (hv in [eV]) :

$$n_i\ r_p \approx 8.52 * 10^{12}\ cm^{-2}\ hv^{-2.5} \qquad (4)$$

Using eqs. 1 and 4 leads to an estimation of the minimal plasma energy :

$$E_{min} \approx 9.2 * 10^{-6}\ r_p\ l\,hv^{2.5} \qquad (5)$$

where E_{min} is in [J]. r_p,l are [cm] and hv in [eV]

The length of the plasma column and the radius will be determined by the constraints given by the respective gas discharge concept. Regardless of other constraints due the gas discharge concept the length must have a certain compared to the initial radius of the plasma column the final radius in order to keep the particle losses due the thermal motion in axial direction small.

A plasma will be presented below where the radius can be estimated to 0 5 mm and the length to 1.2 cm. According to equation 5 the minimum plasma energy is estimated to about 220 mJ for a photon energy of hv = 100 eV. At least the same energy is stored in the magnetic field of the discharge current. which would lead to a total minimum energy of about 0.5 J. For the present device 1.1 J of electrically stored energy is used which is close to this minimal value.

The minimum ion density for such plasma with a radius of $r_p = 0.5$ mm is estimated with eq.4 to $n_i = 3 * 10^{17}$ cm^{-3}. Such density is also observed in the presented EUV-source.

The expression for the minimum line density in equation 4 can also be compared to experimental data for a neon pinch plasma generated in a plasma focus device. which is close to this minimum behaviour and investigated for the emission of photons with energies around 1000 eV.

A detailed discussion of this plasma can be found in Ref.[8]. The spectroscopic investigation of the emission helium- and hydrogen-like neon ions presented there reveal that the plasma is highly transient and close to the minimal criterion given in eq.3. The radius of this plasma is of about $r_p \approx 0.4$ mm. The corresponding ion density can be estimated to $n_i \approx 5 * 10^{18}$ cm^{-3}, which leads to a line density of $n_i\ r_p = 2 * 10^{17}$ cm^{-2}. This is in agreement with the estimation in equation 4, which would lead to $n_i\ r_p = 5 * 10^{17}$ cm^{-2} for a photon energy of hv = 1000 eV.

III. EXPERIMENTAL RESULTS

The plasma is generated in a device where the storage capacitor is directly connected to the electrode system. Omitting a switch allows for a low total inductance below 10 nH of the circuit. Thus energies in the range of 1 J are sufficient to create current pulses having a period time around 100 ns and peak amplitudes in the range of several kiloampere which are required for plasmas emitting in the EUV-range. Details concerning the set-up will be
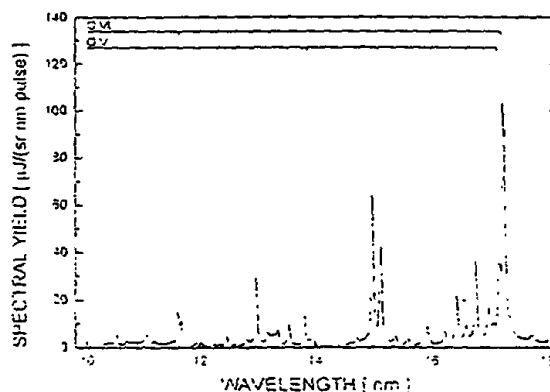

Figure 1. Emission spectrum of synthetic air Transitions of lithium-like (OVI) and beryllium-like (OV) oxygen ions can be identified. Transitions of nitrogen ions can be neglected.

published elsewhere [6].

Figure 1 shows a typical emission spectrum when using oxygen or air in the gas discharge. This spectrum is taken with a flat-field grazing-incidence spectrometer [9] and a calibrated CCD-camera [10] as detector. Transitions of beryllium- and lithium-like oxygen ions can be identified. A spatially resolved measurement of the emission in the EUV-range reveals a radius of about 0.5 mm, which is also assumed for the pinch plasma radius. A neutral gas column with an initial radius of 2.5 mm is used for the present device. Estimating the ion density of the plasma by the observed compression from this value to 0.5 mm leads to $n_i \approx 1.3 \times 10^{17}$ cm^{-3}. This is right of the order of magnitude estimated in eq.4 for a minimal density.

The lifetime of the plasma is assumed to be of the same value like the duration of emission in the EUV range, which has been determined using a fast photodiode in combination with a 1 μm Beryllium filter as transmission window to about 30 ns.

For an equilibrium plasma of the above estimated ion density the electron temperature can be estimated to around 20 eV by the mere observation of lithium-like ions [11]. However, when estimating the electron temperature by the line ratios of different lithium-like transitions values between 30 eV - 40 eV results. These temperatures would lead to helium-like transitions in the equilibrium case according to Ref.[7]. However, helium-like transitions are not observed. This can be referred to the transient behaviour of the investigated plasma, which is also a feature of a minimum plasma according to the above considerations.

The time constant for ionisation from the beryllium- into the lithium-like level can be estimated to $\tau_{Be-Li} = 20$ ns when using the expression for the ionisation rate given in Ref.[7] and assuming an electron temperature of 35 eV and an ion density of $n_i = 1.3 \times 10^{17}$ cm^{-3}. This time constant matches quite well to the observed lifetime of 30 ns. However, the time constant for further ionisation into the helium-like level can be estimated to $\tau_{Li-He} = 100$ ns, which is too slow for achieving this level at the given lifetime. This is in agreement with the lack of helium-like transition in the emission spectrum.

The device has also been operated with sulphur hexafluoride (SF$_6$), neon and argon. The emission spectra will be published elsewhere. The highest ionisation levels taken from the observed emission lines were lithium-like fluorine, beryllium-like neon and sodium-like argon, respectively. From the mere observation of such levels the minimum electron temperature can be estimated to at least 30 eV. This also supports the estimation of a temperature of 35 eV for the oxygen plasma when assuming a similar plasma dynamic and energy input for all gases.

Furthermore, it should be noticed that only transitions of the gaseous elements used for the discharge occur in the emission spectra. This allows to exclude contributions of ablated electrode material.

IV. SUMMARY

A small pinch plasma based radiation source in the EUV-range is discussed in terms of minimal required energy. The results concerning the minimal density, energy and the transient behaviour due to low density of such plasma are in agreement with first experimental results of a gas discharge device, which operates at energies close to the minimal required energy.

The special design of the electrodes [6] allows for a minimal loss of electrically stored energy being converted to the plasma. This device offers a good basis for the development of a high intense radiation source due to the minimal peak power delivered to the electrode system. However, further theoretical and experimental investigations have to be done to discuss the problem in terms of conversion efficiency of electrically to radiated power. A conversion efficiency in the range of at least a few per cent, not yet achieved with the presented set-up, should be achieved for a radiation source for EUV-lithography to guarantee an operation with reasonable average electrical power input not be much higher than about ten kilowatt.

Highly repetitive, extreme-ultraviolet radiation source based on a gas-discharge plasma

Klaus Bergmann, Guido Schriever, Oliver Rosier, Martin Müller, Willi Neff, and Rainer Lebert

An extreme-ultraviolet (EUV) radiation source near the 13-nm wavelength generated in a small (1.1-J) pinch plasma is presented. The ignition of the plasma occurs in a pseudospark-like electrode geometry, which allows for omitting a switch between the storage capacity and the electrode system and for low inductive coupling of the electrically stored energy to the plasma. Thus energies of only a few joules are sufficient to create current pulses in the range of several kiloamperes, which leads to a compression and a heating of the plasmas to electron densities of more than 10^{17} cm^{-3} and temperatures of several tens of electron volts, which is necessary for emission in the EUV range. As an example, the emission spectrum of an oxygen plasma in the 11–18-nm range is presented. Transitions of beryllium- and lithium-like oxygen ions can be identified. Current waveform and time-resolved measurements of the EUV emission are discussed. In initial experiments a repetitive operation at nearly 0.2 kHz could be demonstrated. Additionally, the broadband emission of a xenon plasma generated in a 2.2-J discharge is presented. © 1999 Optical Society of America

OCIS codes: 220.3740, 260.7200, 300.6560, 350.5400.

Introduction

Recent progress in the development of optics in the soft-x-ray and the extreme-ultraviolet (EUV) spectral range has stimulated the investigation of plasma-based EUV sources for laboratory scale applications. One of the most prominent applications is EUV lithography for the future generation of semiconductor devices.[1–3] EUV lithography uses multilayer mirrors and radiation at a wavelength near 13 nm. Structuring on the 10-nm scale has already been successfully demonstrated with laser-produced plasmas.[4,5] However, with laser-produced plasmas there are still problems to solve with respect to debris, when solid or liquid targets are used, and the supply of powerful lasers to fulfill the demands of a commercially usable radiation source. Recently this has lead to activities in the field of gas-discharge

plasmas as sources for EUV radiation based on, e.g., a capillary discharge or a gas puff Z-pinch.[6–8] Although gas-discharge plasmas offer the advantages of a reduced debris problem and more compact and lower-cost devices, there are still problems in achieving the required lifetime and the average emitted power or the required repetition rate. In this study a gas-discharge plasma is presented for which the above problems seem to be solvable, owing to the special design of the electrodes. The spatially defined ignition of the plasma required in all pinch plasma devices is achieved by use of a pseudospark-like electrode geometry. The volume is defined by two opposing holes in each electrode as shown in Fig. 1. The ignition is driven on the left-hand branch of the Paschen curve, with preference given to the long path of the electrical-field lines that extend through the boreholes. In contrast to other concepts such as the capillary discharge or a Z-pinch this device makes use of a self-igniting plasma. This means that the storage capacitor is directly connected to the electrode system and that the plasma is ignited when the capacitor is charged with the ignition voltage. The plasma ignition is discussed in detail in Ref. 9. The other concepts require a switch between the storage capacity and the electrode system to ensure that the storage capacity can be charged to the required energy. Operating the presented device on the left-

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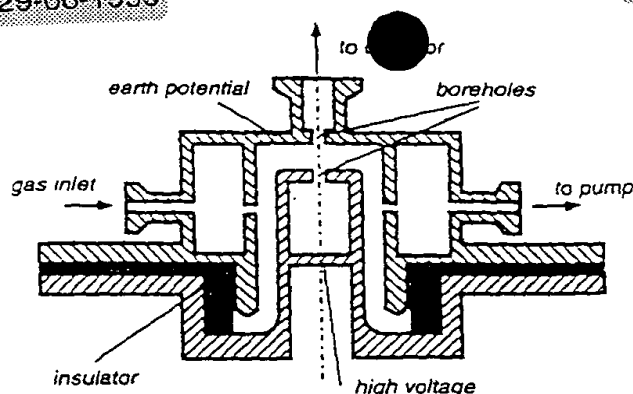
Fig. 1. Scheme of the electrode system. The electrodes are integrated in a storage capacitor made by two opposing disks.
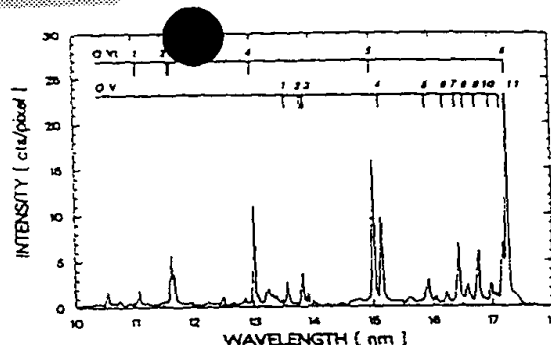

Fig. 2. Emission spectrum of an oxygen plasma (CCD camera readout). The indicated transitions of beryllium- and lithium-like ions are listed separately in Table 1.

hand branch of the Paschen curve allows us to charge the capacitor and the electrode systems to sufficiently high voltages in the range of at least several kilovolts, which is required for such pulsed gas-discharge sources. In the present device a pulsed current is used to compress the plasma that has built up on the symmetry axis to densities and temperatures necessary for the emission of radiation in the EUV range. Since the storage capacitor is directly connected to the electrode system, a low inductive coupling of the electrically stored energy to the plasma can be achieved. Thus electrical energies in the range of only a few joules are sufficient to create the necessary current pulses. These low energies and the avoidance of contact of the igniting plasma with, e.g., the insulator, as in the capillary discharge or the electrodes, promises a high system lifetime and the achievement of high repetition rates in the range of several kilohertz.

2. Experimental Setup

The experiments were carried out with an electrode system as shown schematically in Fig. 1. The borehole diameter is 5 mm, and the gap distance in the vicinity of the boreholes is 6 mm. The discharge is operated in a homogeneous pressure environment in the range of several pascals, depending on the gas used. The electrodes are integrated in a disk capacitor consisting of two aluminium plates with a capacity of 20 nF. The inductance of the setup can be estimated from the current measurements shown below to ~6 nH. The discharge is driven in a self-igniting mode at voltages in the range of several kilovolts. When oxygen is used, the electrode geometry under investigation leads to a pressure of ~10 Pa. The plasma column, which is compressed by the current, extends through both boreholes and across the electrode gap and is assumed to have a length of ~12 mm.

EUV spectra were recorded with a flat-field grazing incidence spectrograph[10] in combination with a CCD camera as detector. Both were calibrated with synchrotron radiation. The reflectivity of the grating is

~18% in the wavelength range of interest. The spectrograph has a resolution of $\lambda/\Delta\lambda \approx 300$. Calibration data of the CCD chip are published elsewhere.[11] Spatially resolved measurements of the spectral lines were performed with the flat-field spectrograph in combination with a 150-μm slit perpendicular to the entrance slit of the spectrograph. This leads to a one-dimensional image of the source in the axial direction, which is assumed to have a cylindrical symmetry. *lower*

Time-resolved measurements of the EUV emission were performed with a fast photodiode with a temporal resolution *lower* than 10 ns in combination with a beryllium filter of 1-μm thickness, which restricts the transmitted light to the spectral range of interest. The beryllium offers a transmission window in the spectral range between the absorption K edge at 11.2 nm (36% transmission) to the highest wavelength recorded with the spectrograph at ~17 nm (6%).

The current waveform was determined with a magnetic probe that was inserted into the plates of the storage capacitor.

3. Results and Discussion

A. Extreme-Ultraviolet Emission of an Oxygen Plasma

Figure 2 shows a spectrum of an oxygen plasma produced in a discharge of 1.1-J electrical energy. Transitions of beryllium-like (O v) and lithium-like (O vi) ions can be observed. The transitions indicated in Fig. 2 are listed in Table 1. To get the spectral characteristics at the emitting region, the absorption in the spectrograph (80 cm) in an atmosphere of 10-Pa oxygen has to be considered. Figure 3 shows the spatial profile of the lithium-like O vi $2p$–$4d$ transition. The profile has an approximately Gaussian shape with a radius (FWHM) of ~470 μm. The total energy emitted into this line in the axial direction is ~60 μJ/(4π sr). The source sizes for the other transitions are similar compared with the O vi $2p$–$4d$ transition. Also, in the visible spectral range the plasma exhibits a diameter of ~1 mm. The ion density is estimated by assuming that the plasma

F2

T1

F3

Line	Wavelength (nm)	Transition
O vi—1	11.02	$2p$–$6d$
O vi—2	11.58	$2s$–$4p$
O vi—3	11.64	$2p$–$5d$
O vi—4	12.98	$2p$–$4d$
O vi—5	15.01	$2s$–$3p$
O vi—6	17.31	$2p$–$3d$
O v—1	13.55	$2s^2$–$2s4p$
O v—2	13.81	$2s2p$–$2s5d$
O v—3	13.90	$2s^2$–$2p3d$
O v—4	15.15	$2s2p$–$2s4d$
O v—5	15.89	$2p^2$–$2p4d$
O v—6	16.26	$2p^2$–$2p4d$
O v—7	16.46	$2s2p$–$2p3p$
O v—8	16.50	$2p^2$–$2p4d$
O v—9	16.80	$2s2p$–$2s4d$
O v—10	17.02	$2s2p$–$2s4d$
O v—11	17.22	$2s^2$–$2s3p$

"Wavelengths for split transitions refer to an average value.

with an initial diameter given by the borehole extension of 5 mm is compressed to ~1 mm in diameter. This leads to an ion density of $n_i \approx 1.3 \times 10^{17}$ cm^{-3} and an electron density of $n_e \approx 6 \times 10^{17}$ cm^{-3} when assuming a plasma in the lithium-like ionization level. Determining the electron temperature by the line ratios of the lithium-like transitions ($2p$–$4d/2p$–$3d$) and ($2p$–$4d/2s$–$3p$) and assuming a line intensity proportional to $I \propto n_e n_i^l f_{ik} \exp(-\Delta E/T_e)/\sqrt{T_e}$ as in the corona model (n_i^l density of the lower level, f_{ik} oscillator strength, ΔE energy gap of the transition), the electron temperature is estimated to be approximately $T_e \approx 35$ eV.

The EUV emission recorded with the fast photodiode and the respective current waveform (dI/dt) are shown in Fig. 4. The EUV emission has a duration of ~30 ns and starts ~30 ns after the onset of the discharge. The emission is correlated with a dip in the current waveform, which is referred to as the increase of the inductance of the collapsing plasma column.
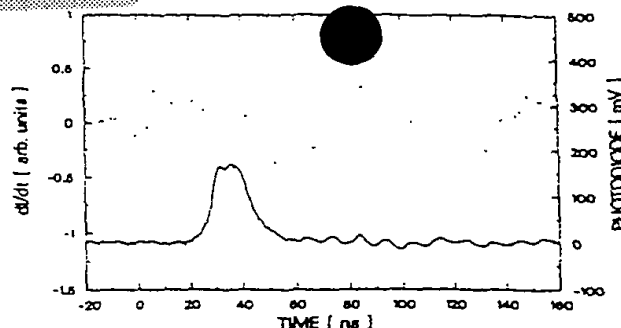
In an equilibrium plasma an electron temperature

Fig. 4. Current pulse (dI/dt) and the respective EUV emission (lower curve) recorded with a fast photodiode in combination with a 1-μm beryllium filter.

of $T_e \approx 35$ eV would lead to an ionization into the helium-like level.[12] In the present case, however, the helium-like level will not be effectively achieved, since the time constant for ionization into this level, τ_{He}, is estimated to be large compared with the lifetime of the plasma, which is indicated by the photodiode measurements in the range of 30 ns. According to the ionization rates given in Ref. 13 the time constant for ionization from the beryllium-like level into the lithium-like level would be $\tau_{Li} = 20$ ns and for further ionization into the helium-like level $\tau_{He} = 100$ ns. This means that only the lithium-like level can be effectively achieved as observed in the emission spectrum. For the calculations of the ionization rates an electron temperature of 35 eV and an ion density of 10^{17} cm^{-3} were assumed.

B. Current Waveform

To estimate the electrical circuit parameters, the current waveform shown in Fig. 4 was fitted, assuming an oscillation circuit with a varying inductance $L_p(t)$ of the plasma column and a varying resistance $R_p(t)$ that obeys the equation

$$[L_0 + L_p(t)]\frac{d^2Q}{dt^2} + \left[R_p(t) + \frac{dL_p(t)}{dt}\right]\frac{dQ}{dt} + \frac{Q}{C} = 0. \quad (1)$$

Q is the charge of the storage capacity, and L_0 is the nonvarying part of the device inductance. The current is given by $I(t) = -dQ(t)/dt$. The measured current waveform and the fit according to the above equation are shown in Fig. 5. The inductance is determined to be approximately $L_0 = 6.2$ nH. The current amplitude at the instance of maximum compression is given by $I_{max} \cong 12.8$ kA. The resistance $R_p(t) = R_s(t) + R_0$ of the plasma and the remaining part of the device is assumed to have a constant contribution of $R_0 = 55.7$ mΩ, which describes the damping at higher periods, and a varying contribution $R_s(t)$, which describes the decrease of the plasma resistance at the beginning of the discharge on the 10-ns time scale. The evolution of this part of the resistance depends on the current and can be qualitatively described by the laws known from high-
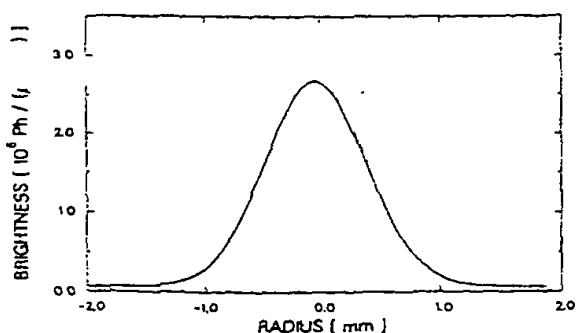
F5

Fig. 3 Spatial profile of the lithium-like $2p$–$4d$ transition at 13 n. Dotted curve, measured profile. Solid line, fit of the profile with a Gaussian distribution.
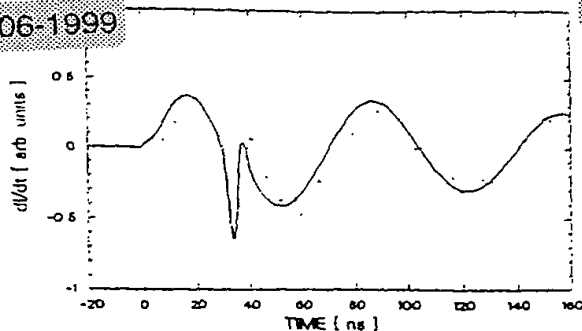
Fig. 5. Measured dI/dt signal (dotted curve) and the respective simulation (solid curve) based on a damped oscillating circuit with varying inductance that is due to the plasma dynamics.
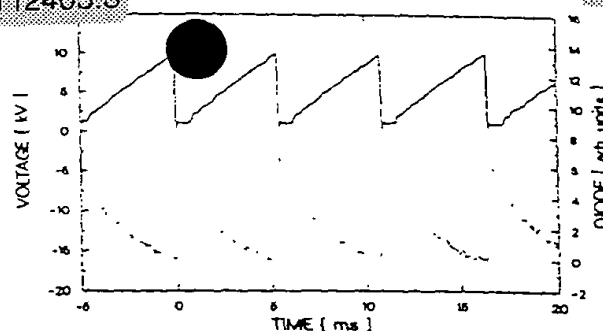

Fig. 6. Repetitive operation at 0.2 kHz. Solid curve, charging voltage of the storage capacity. Dotted curve, EUV diode signal, which is electronically prolonged.

pressure sparks.[14] For simplicity, a Toepler-like dependence[15] was assumed in the present case with $R_s = 2.5 \times 10^{-5}$ Vs$^{}$/$\int I(t)dt$ for the first half period of the current pulse and set to zero for higher times.

The varying inductance $L_p(t)$ is assumed to be caused by a contracting and expanding plasma column with a length of ~12 mm. The fit of the current waveform then allows us to estimate the ratio v/r_{min}, where v is the velocity of the outer sheath of the plasma column and r_{min} is the radius at the instant of maximum compression. In the present case the calculation leads to $v/r_{min} \approx 2.3 \times 10^8$ s^{-1}. When we take the radius from the spatial line profile measurements to be $r_{min} \approx 470$ μm, the velocity and the respective ion kinetic energy ($e_{kin} = m_i v^2/2$) can be estimated to be approximately $e_{kin} \approx 1$ keV.

This crude discussion of the plasma dynamics and the estimation of the related ion kinetic energy is in agreement with the picture of a dynamic pinch plasma, in which heating results from thermalization of the kinetic energy of the collapsing ion column. The electrons are heated by hot ions to the required temperature, and subsequently the plasma decays, owing to hydrodynamic expansion. In this picture the ionization potential of the lithium-like oxygen level needs an electron temperature of ~35 eV in this transient plasma, which could result if the ion kinetic energy were at least ~0.5 keV.

C. Repetitive Operation

We can drive the discharge repetitively by simply charging the storage capacity with a constant current. An example is shown in Fig. 6 for a repetition rate of nearly 0.2 kHz. There the upper curve shows the voltage across the electrodes. In the present case the discharge ignites at a voltage of 10 kV. The lower curve shows the EUV-diode signal, which is electronically prolonged to make the 30-ns event visible on the millisecond time scale in Fig. 6. The data give an impression of the reproducibility of the EUV emission and the igniting voltage of the discharge, which is driven in a self-igniting mode. In the present case the repetition rate is limited by the available power supply. Repetition rates in the range of several kilohertz

seem to be achievable when compared with pseudo-spark switches operated at comparable peak currents and charge transfers as, e.g., described in Ref. 16. The mechanism of the ignition of the plasma in the described EUV source is the same as in pseudospark switches, owing to a similar electrode geometry. The mechanism of the ignition is described in Ref. 9. However, when the setup is used as a switch, which is connected to a load, where most of the electrical energy is consumed, a high lifetime is achieved by generation of a diffuse plasma that covers a large electrode area. In the EUV source a plasma of a much higher energy density than in pseudospark switches is generated by the pinch effect. This plasma, however, has no contact with the electrode surface. Thus the lifetime data known from the pseudospark switches cannot be transferred to the present setup, and lifetime investigations have to be the subject of future investigations. After a preliminary experiment of continuous operation for 1 h at a repetition rate of 100 Hz and a pulse energy of 1.1 J without water cooling, no decrease of the performance nor erosion of the electrodes was observed.

D. Broadband Emission of a Xenon Plasma

Up to now the discharge has been operated with different gases such as argon, neon, air, sulphur hexaflouride, or xenon, which leads to different spectral characteristics in the EUV range. The results will be published elsewhere. From the technological point of view the broadband emission of xenon near 13 nm, which has been observed in gas discharges and also laser-produced plasmas,[7,17] is of special interest.

Figure 7 shows a xenon spectrum produced in a discharge of 2.2 J of electrical energy with a slightly different setup compared with the experiments discussed above. In this case a silicon-nitride window with a thickness of 150 nm (absorption edge at 12.4 nm) was used to divide the gas-discharge region from an evacuated environment. This allows us to suppress the strong absorption of the neutral xenon gas near 13 nm inside the spectrograph. Transitions of at least ten-times-ionized xenon (Xe XI) can be identified in the emission spectrum.[7,17,18] According to
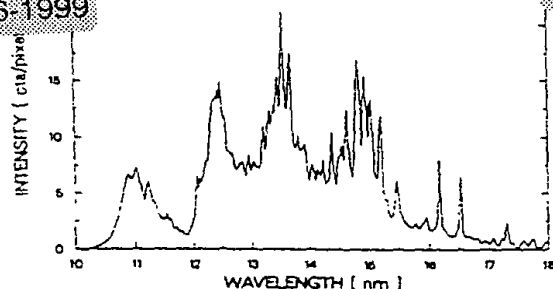
Fig. 7. Emission spectrum of xenon behind a 150-nm silicon nitride window. Transitions of at least ten-times ionized xenon (Xe xi) can be identified.

the data given in these references the lines at 16.2 and 16.5 nm arise from transitions of Xe ix ($4d^{10}$–$4d^{9}5p$). The group between 14 and 15.2 nm shows transition of Xe x ($4d^{9}$–$4d^{8}5p$). The lines between 13 and 14 nm are attributed to transitions of Xe xi. According to Ref. 17 the minimum electron temperature can be estimated to approximately $T_e = 35$ eV from the appearance of the Xe xi ionization level.

4. Conclusion

A new, to our knowledge, kind of pinch plasma EUV radiation source at wavelengths near 13 nm is presented. The special design of the electrodes allows for a low inductive coupling (inductance is below 10 nH) of the electrical energy to the plasma and for omission of a switch between the storage capacitor and the electrode system. Thus energies of only 1 J are sufficient to generate a current pulse that is necessary for a pinch plasma emitting in the EUV range. The electrode design and these low pulse energies lead to a low electrode erosion and allow for a highly repetitive operation, which is prerequisite to a long lifetime and to the achievement of a high average power of emitted radiation. With the present device more than 10^{6} shots have been performed without any damage to the electrodes or deterioration of the device performance. This low erosion also means a reduced debris problem, especially in comparison with laser-produced plasma with a solid or a liquid target.

The concept is discussed by the example of an oxygen plasma generated in a discharge of 1.1 J electrical energy. In this case the EUV emission consists of distinct lines near 13 nm that arise from transitions of beryllium- and lithium-like ions. Broadband emission can be achieved with a discharge in xenon, in which transitions of at least ten-times-ionized xenon lead to a band of lines in the spectral range of approximately 10–16 nm.

With respect to a device with high average emitted power, future investigations will be focused on increasing the conversion efficiency and on the study of the behavior of the electrode erosion and the holdoff voltage capability at high electrical power and at higher repetition rates.

An extreme ultraviolet radiation source based on a gas discharge plasma

1) introduction

2) EUV - lithography

3) minimal pinch plasma

4) gas discharge parameters

5) EUV - emission (oxygen)

6) current waveform

7) EUV - emission (SF_6, Ne)

8) repetitive operation

9) EUV - source

(1) introduction

Thank you for the introduction. Good morning ladies and gentlemen. The session now turns to smaller pulsed power devices for the generation of pulsed radiation. I would like to present a small pinch plasma device as a radiation source for the extreme ultraviolet radiation range. The driven force for our activities is to supply a radiation source for the extreme lithography which might be the successor of the current deep ultraviolet lithography. In this talk first results of a gas discharge based radiation source are presented. Most of the experiments, which give information concerning the plasma dynamics have been done with oxygen. I would like to present the emission in the EUV-range and some further time resolved measurements and give some estimation of the plasma parameters. We also operated the discharge with other gases, where first results are also shown. I would like to close with the demonstration of high repetitive capability and some preliminary data concerning average emitted power.

) EUV - lithography

As already mentioned we are investigation a gas discharge plasma source in terms of being suitable as radiation in the EUV-lithography. The principle of this technique is shown in this picture. Like in the current deep UV-lithography a mask is imaged onto a photo resist to create the desired structures. In this case, a system of Bragg-mirrors operating at a wavelength around 13 nm or 11 nm is used dependent on the mirror material. This allows to create limited by diffraction structures far below hundred nanometer. This has already been shown. In an Intel study structure sizes of 70 nm are reported. Here, an example from Sandia National Lab in Livermore, in this case about 130 nm structure size.

For a radiation source the main interest has been focused on laser produced plasmas as indicated also in this picture. However, the interest in gas discharge sources has increased rapidly in the recent past, where gas discharge sources offer the principle advantage of lower costs and reduced debris problem due to operating with a gas target. There is especially progress concerning the achievement of the required high repetition rate or the average power, which have been considered as the main drawbacks.

EUV - lithography a radiation source is required that emits in the range of several Watt into 2π at a wavelength around 13 nm in a bandwidth of about 2 %. These estimation is taken from an elder reference using these assumptions concerning the throughput, the resist sensibility, the number of mirrors and the reflectivity and also the solid angle of the condensor optics. There might be some more sophisticated assumptions concerning the source requirements, which will, however, not lead to essential different values.

Our source development is orientated at the aim of producing a plasma as emitter in the EUV-range with the smallest possible energy per pulse or with the smallest peak power delivered to the electrode system. Thus the access to high repetition rates - we are talking about several kilohertz, are easier accessible. Also the problems with erosion seems to be easier solvable when operating with a minimum peak power.

(3) minimal pinch plasma

Now, what is the smallest amount of energy that is necessary to create a plasma that emits radiation in the EUV - range, or as considered here more general photons with energy hv. Let me shortly summarize these consideration, which will be explained in detail in the proceedings paper. Starting point is a plasma based on a dynamic pinch plasma, where an amount of gas is heated and compressed by the self magnetic field of a discharge current flowing through this plasma. The main energy input is assumed to come from the ion kinetic energy that is accumulated in the compression phase. The plasma is characterized by different parameters, namely length, radius, electron temperature, ion density or the degree of ionisation. The energy within this plasma is than given by this expression, simply the number of ions and the minimal required energy per ion, that consists of the thermal plasma energy, the potential energy of the ionisation level and energy to excite the ions, here simply estimated by this hv. Using these further assumptions concerning the relation between photon energy, temperature and degree of ionisation allows to express the term in brackets as a function of the photon energy. The minimum criterion is based on the question of the minimum number density necessary within such plasma. The density determines, how fast the ion kinetic energy is converted to thermal electron temperature and radiation. The time constants for these processes should be lower than the lifetime of the plasma, which leads to a minimal density. Here, we assume the ionisation time constant into the required level should be of the order of the lifetime, which leads to an estimation for the product of radius and ion density.

Finally, we have this for the minimal energy, where the plasma radius and the length is determined by the respective gas discharge concept. I am going to present a plasma with radius 0.5 mm and a length of 12 mm. This would lead to about 220 mJ for a photon energy of 100 eV. At least the same amount will be stored in the magnetic field. So the respective minimum device will have a storage energy of half a Joule. In fact experimental results of a 1 Joule plasma will be presented, where especially this criterion of similar time scales for ionisation and lifetime can be deduced from the experimental results.

(4) gas discharge parameters

Lets now look at the experimental results. The plasma is generated in a fast discharge of a charged capacitor. Typical energy is in the range of one Joule, where I would like to present results achieved with 1.1 J. The low inductive coupling of the storage capacity to the electrode system leads to a peak current around 13 kA and period times below hundred nanoseconds. The total inductance is below 10 nH. A neutral gas column of 12 mm length and 5 mm initial diameter is compressed and heated by this pulsed current to the required plasma parameters for emission in the EUV-range. I would like to discuss in more details experimental results where oxygen has been used for the discharge. In this case, the neutral gas density is around $5 \, 10^{17} cm^{-3}$.

(5) EUV - emission (oxygen)

A typical emission spectrum is shown here. All the observed lines can be identified as transitions of beryllium- and lithium-like oxygen ions. A few are indicated in this spectrum, for example this series of lithium-like ions 2p-3d, -4d, -5d. This spectrum was recorded with a flat-field grazing incidence spectrograph and a CCD-camera as detector. Both have been calibrated using synchrotron radiation what allows to give absolute values.

A spatially resolved measurement of the source in·this line at 13 nm is shown here. This pictures refers to the source size when looking in axial direction. The diameter in this wavelength is about 900 micrometer. Similar values are observed for the total EUV-range and also for the visible spectral range. So this diameter is also assumed for the plasma. The electron density can be estimated when considering the compression from the initial diameter to these 900 microns. This leads to around $6\ 10^{17}$ cm^{-3}. When determining the electron temperature from these line ratios of different lithium-like transitions values between 30 and 40 eV result. This temperature would be about a factor of two too large when considering a plasma in thermal equilibrium, where the lithium-like level has its maximum abundance at a temperature of 20 eV . Between 30 and 40 eV the helium-like level would be dominant, which is, However, not observed in the emission spectrum. This is referred to the transient behavior of the plasma. Experimental results, which support these temperature estimations and the transient behavior will be presented now.

(6) current waveform

Here some results of time resolved measurements. The upper curve shows the I-dot signal with this characteristic peak. This peak is referred to the increase of the inductance due to the contraction of the plasma column. Below is the emission in the EUV-range which has been recorded using a fast photo diode in combination with a one micron beryllium window. The emission coincides with the dip in the I-dot signal which supports the model of a dynamic pinch plasma.

The current signal allows to estimate the ratio of the compression velocity of the plasma column and the radius at the instant of maximum compression. Fitting the current signal the assumption of a varying inductance then leads to this value of $2\ 10^{8}$ s^{-1}. Taking the results from the spatially resolved measurements leads to around 1 keV for the ion kinetic energy achieved in the compression phase. This is at least sufficient to heat up an oxygen plasma to the lithium-like level with temperatures up to 40 kV estimated from the line ratios.

No some remarks to the transient behavior. The lifetime of the plasma is assumed to be equal to the duration of emission in the EUV-range, the 30 ns's. For this density and 35 eV electron temperature about 20 ns can be estimated for the time constant for ionizing from the beryllium- to the lithium-like level. Around 100 ns result for the time constant for further ionizing into the helium-like level. This can explain the lack of helium-like transition in the spectrum. The ionization into this level even at this high electron temperature is too slow compared to the observed lifetime.

(7) EUV - emission (SF$_6$, Ne)

Here some further results, which confirm that electron temperatures of at least 30 eV can be achieved. We investigated the emission of different gases. These two spectra show emission spectra of elements which are close to oxygen in the atomic number. This is the emission spectrum when using sulphur-hexafluoride. Nearly all the observed lines can be referred to transitions of fluorine ions in different ionization levels. The highest level is the lithium-like level indicated as F VII here. Here also lines from beryllium- and boron-like fluorine ions.

When using neon the highest ionization level is beryllium-like neon (Ne VII). In this emission spectrum lines from levels starting with the nitrogen-like neon ions can be observed. From the mere observation of the highest ionization levels and considering an equilibrium plasma the lower limit of the electron temperature can be estimated. This leads to values around 30 eV when only considering these two emission spectra.

This is what I have concerning the basic investigations of the plasma. I would like to close with some aspects, which are of importance for the technological point of view.

(8) repetitive operation

Here a result concerning repetitive operation. The low energies required per pulse allow for a highly repetitive operation. In this case of the 200 Hz we are limited by the available power supply. What is really the limit will be the scope of further investigations. The upper curve shows the charging process and the voltage of the storage capacity. Here with the breakdown of the voltage the discharge takes place on a 100 ns time scale, which is not resolved in this picture. Below is the diode signal indicating the EUV-emission. The signal has been prolonged electronically to make it visible on this millisecond time scale.

(9) EUV - source

The average emitted power when operating at 200 Hz is shown here. This is a picture of the device. Here the rack with the power supply and the control unit. This contains the storage capacity and the electrode system. The radiation is observed via this flange. The maximum average emission in a single line at 12.8 nm is given here. 70 mW into 4π in axial direction for a fluorine transition. Below is the maximum for broadband emission at a wavelength around 11 nm when using xenon.

These values are not sufficient for a radiation source used in EUV-lithography for production, but already useful for metrology applications at the considered wavelengths. This is what I have for today - Let me close and thank you for your attention.

12th IEEE Pulsed Power Conference, 1999 - Monterey, California

An extreme ultraviolet radiation source based on a gas discharge plasma

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* extreme ultraviolet (EUV) lithography

* EUV - emission of oxygen

* plasma parameter

* EUV - emission of SF_6, Ne

* repetitive operation

EUV - lithography
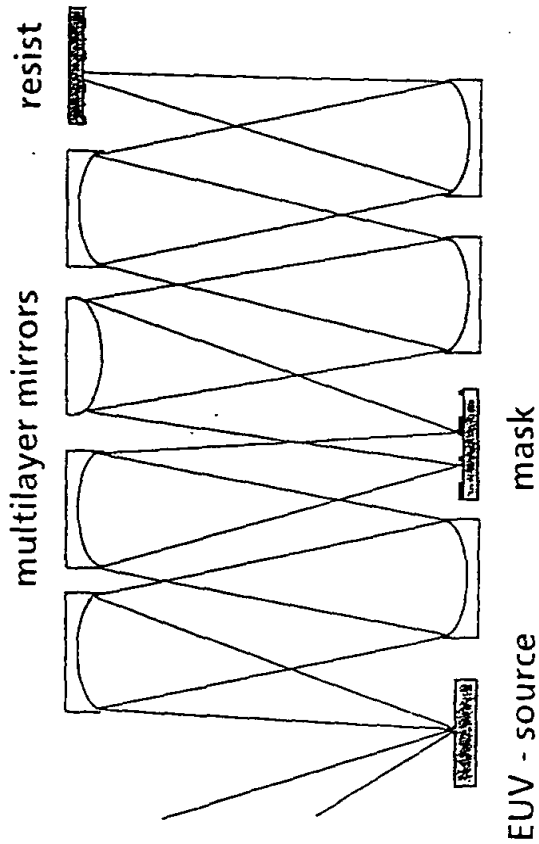
demands on source* :

$$P_s \approx 4 \ W/(2\pi sr)$$

at 13 nm in 2% bandwidth

assumptions :

* throughput : 2.5 cm²/s
* resist : 2.5 mJ/cm²
* 8 mirrors : 75%
* 3 windows : 70%
* cond. optic : 0.2 sr

resist

multilayer mirrors

mask

EUV - source

courtesy . http://www.ca.sandia.gov/news/euvl

minimum pinch plasma

$$E_{min} \approx 9.2 * 10^{-6}\, r_p\, l_p\, h\nu^{2.8}$$

E_{min} in [J],
$h\nu$ in [eV],
r_p, l_p in [cm]

example :

$r_p = 0.5$ mm
$l_p = 12$ mm
$h\nu = 100$ eV

$$\Rightarrow E_{min} \approx 220\ mJ$$

$<Z>, n_i, T_e$

l_p

r_p
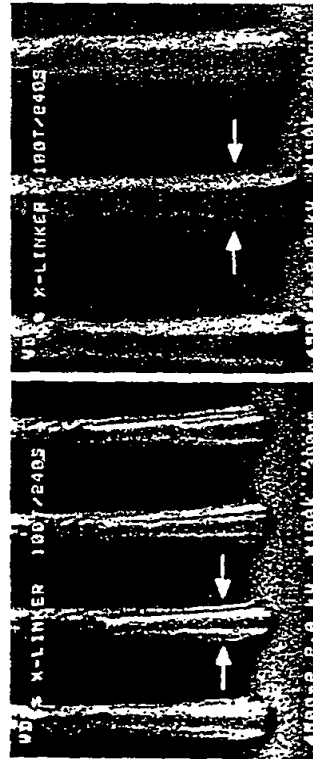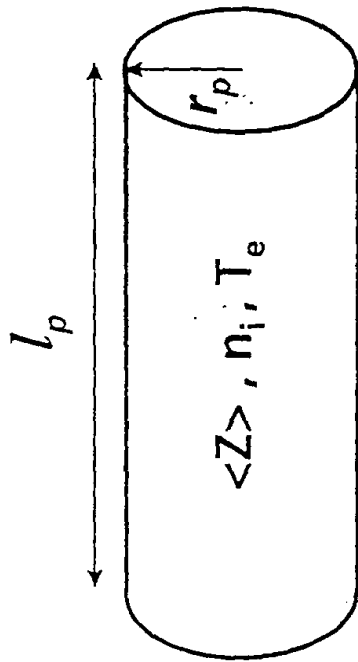
$$E_{min} = \left\{ ((\langle Z\rangle +1) * T_e + E_{pot} + h\nu \right\} \pi r_p^2 l_p n_i$$

* $h\nu \approx 3 * T_e$
* $h\nu \approx 3/4\ Ry\ \langle Z\rangle^2$
* $E_{pot} \approx Ry\ \langle Z\rangle^{2.5}$
* $\tau_{ion} \approx \tau_{life} \Rightarrow n_i * r_p$

gas discharge parameters

$$\vec{f} = \vec{j} \times \vec{B}$$

I

storage capacity

power supply
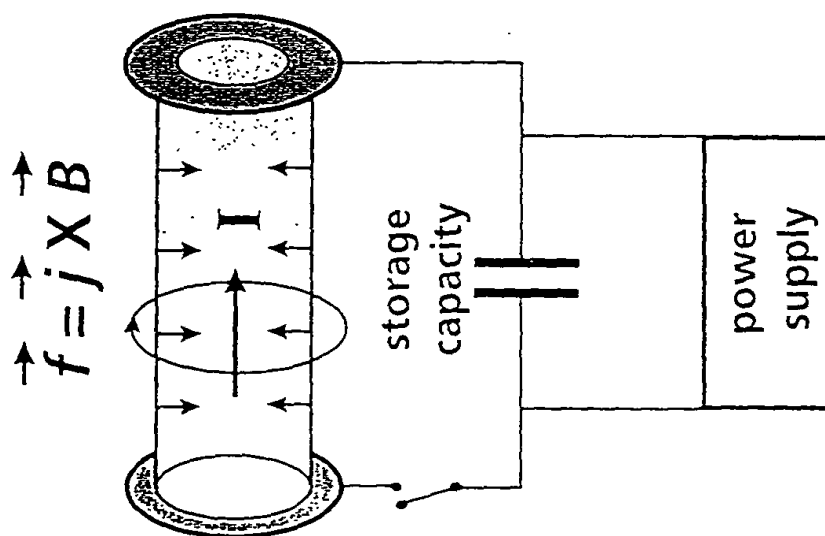
electrical circuit :

pulse energy	: 1.1 J
peak current	: 13 kA
period time	: 80 ns

neutral gas column :

element	: O_2
density	: $5*10^{15}$ cm^{-3}
length	: 12 mm
diameter	: 5 mm

EUV - emission (oxygen)

spatial profile OVI 2p-4d
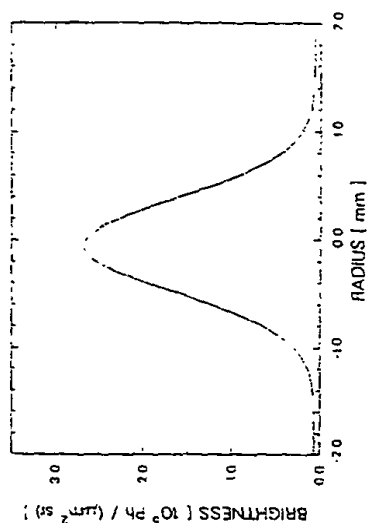
$\rightarrow n_e \approx 6 * 10^{17} cm^{-3}$
from compression

$r_p \approx 450 \mu m$

$\rightarrow T_e \approx 30 - 40$ eV
from line ratios
OVI 2p-4d / 2p-3d
OVI 2p-4d / 2s-3p
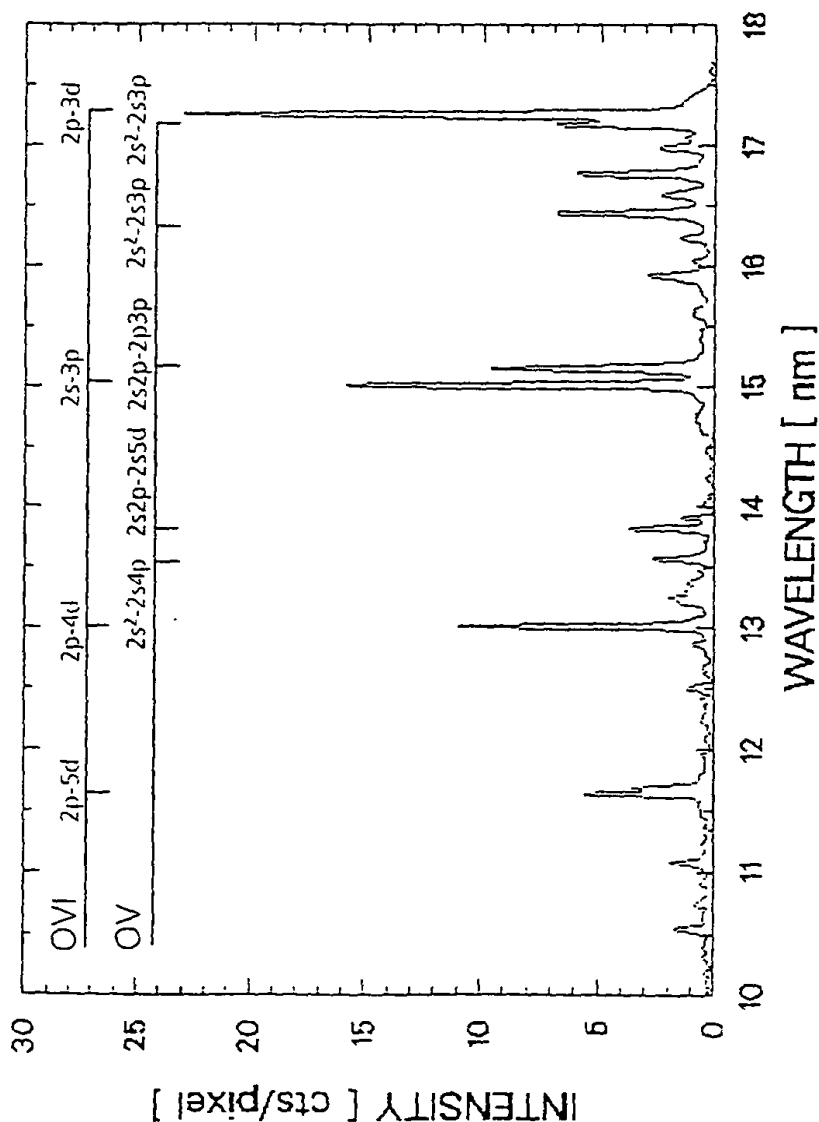
current waveform
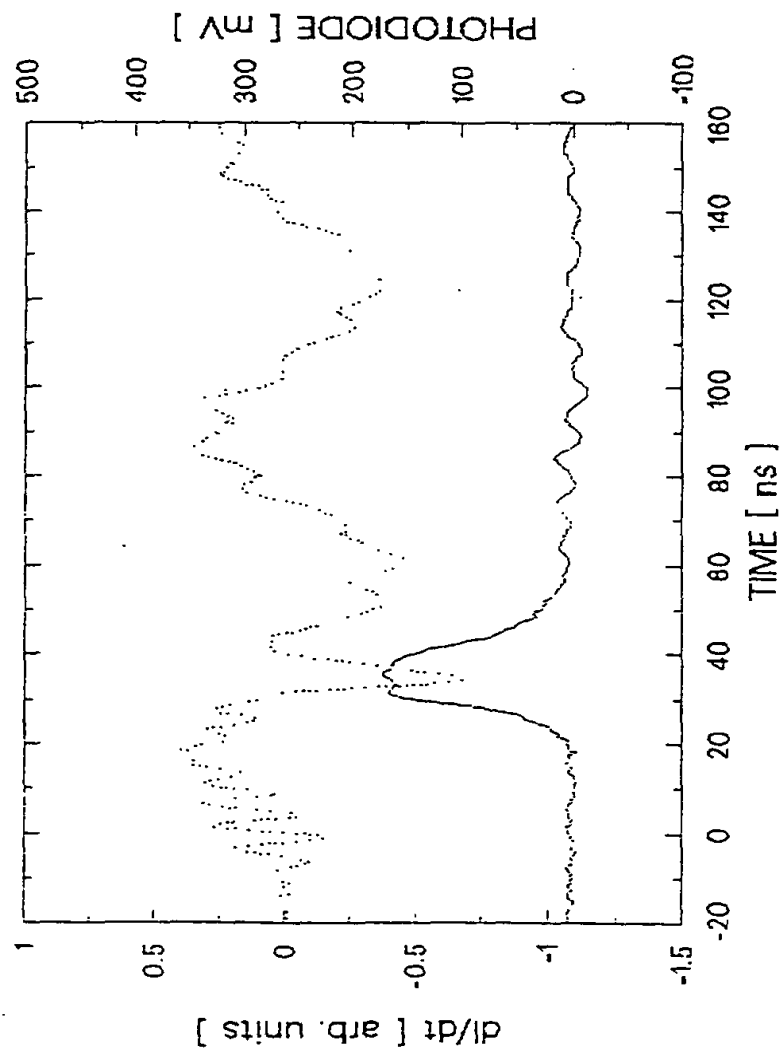
from dI/dt:

$$\frac{\dot{L}_{max}}{L_0} = \frac{V_s}{r_p} \approx 2.3 \cdot 10^8 \, s^{-1}$$

$$r_p \leq 450 \, \mu m:$$

$$E_{kin} = \frac{m_i}{2} V_s^2 \leq 980 \, eV$$

from diode signal:

$$\tau_{life} \approx 30 \text{ ns}$$

ionisation time constant:

$$n_i = 10^{17} cm^{-3}, \ T_e = 35 \, eV$$

$$\tau_{Be-Li} \approx 20 \text{ ns}$$
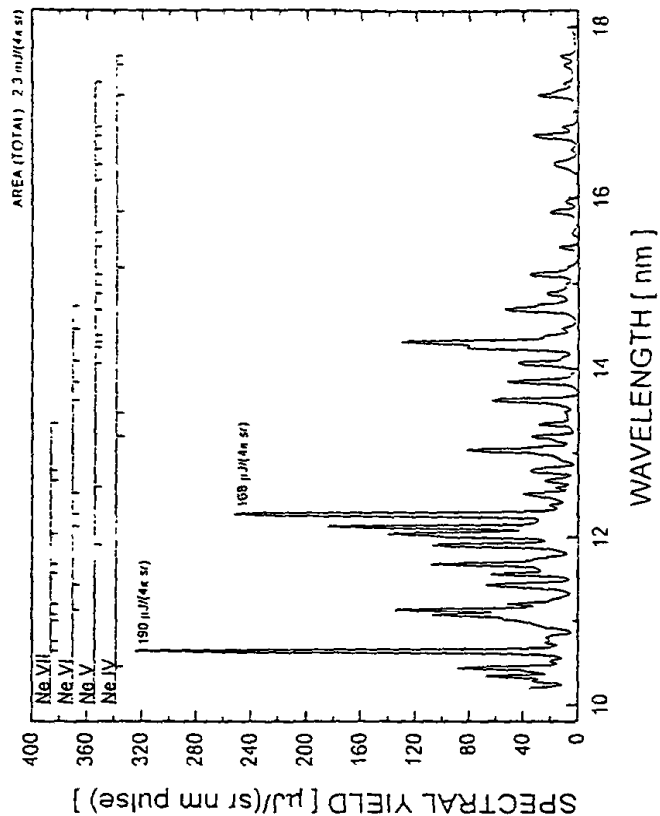
$$\tau_{Li-He} \approx 100 \text{ ns}$$

PHOTODIODE [mV]

dI/dt [arb. units]

TIME [ns]

- 25 -
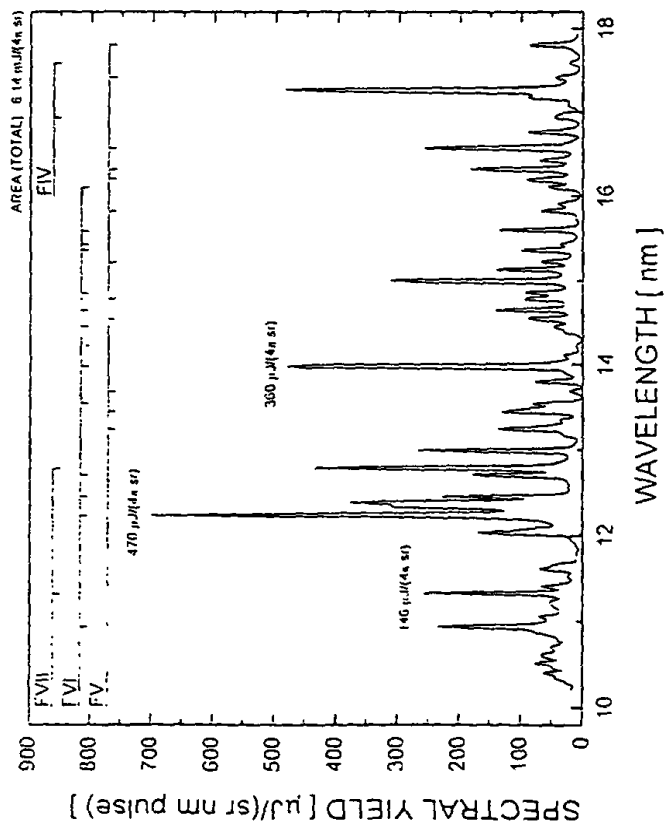
EUV - emission (SF₆, Ne)
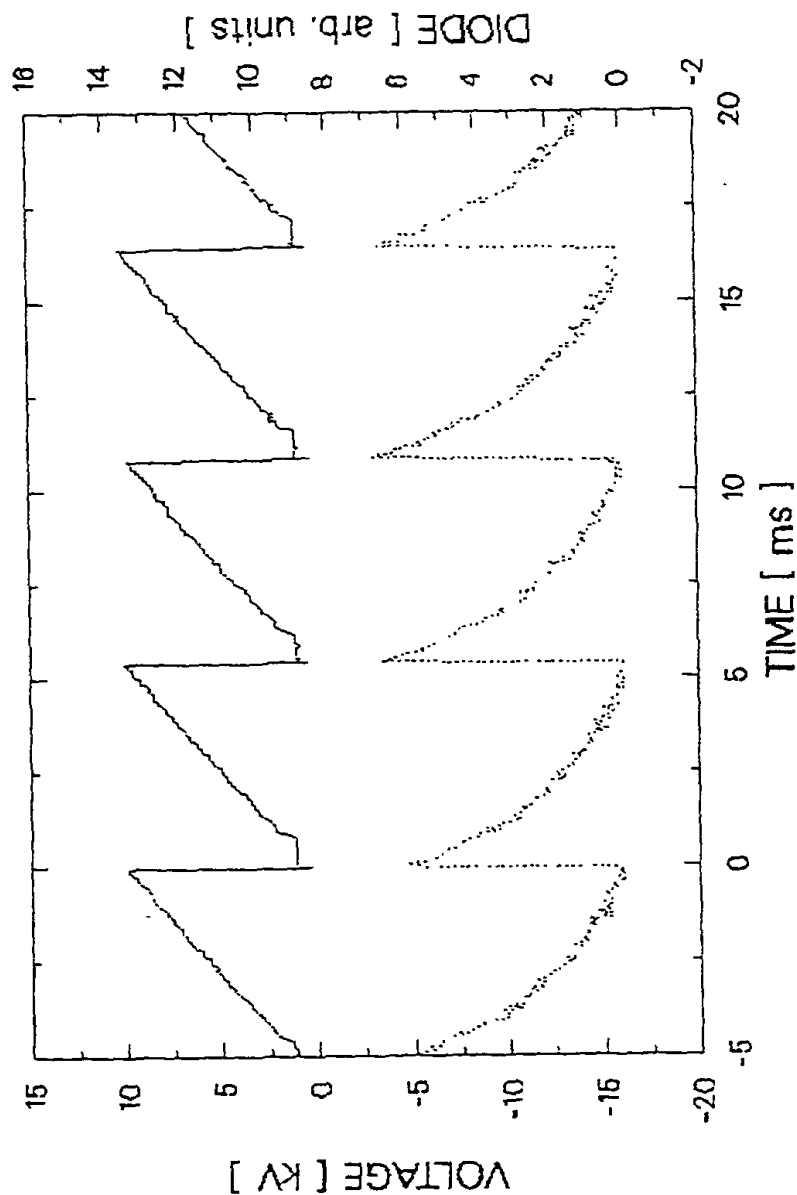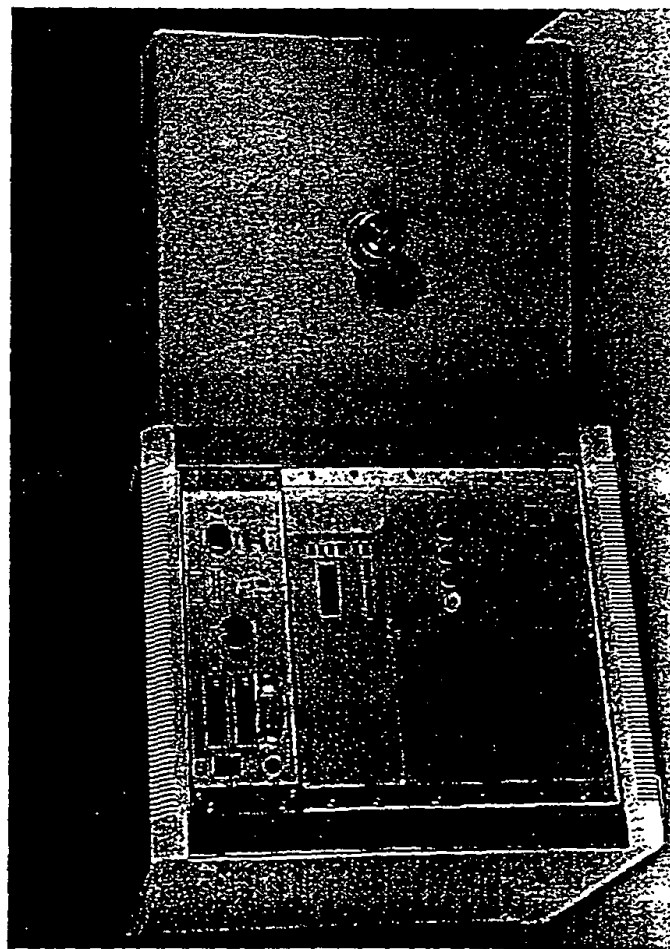
- 26

repetitive operation (200 Hz)

EUV - source

currently achieved :

rep.-rate   : 200 Hz
lifetime   : > 10⁷ pulses

average emitted power :

70 mW / $4\pi sr$
fluorine : 12.8 nm (line)

1.3 W / $4\pi sr$
xenon : 11nm (1 nm b.w.)